Target Layering for Inertial Fusion Energy

A White Paper prepared for the IFE Community Workshop

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1. Executive Summary

Inertial Fusion Energy (IFE) power plants will require ignition and burn of deuterium-tritium (DT)–filled fusion targets at an expected rate of ~5–10 per second. The focus of this paper is the technology required to provide layered targets to an IFE plant at the required rate and with sufficient fuel layer uniformity to ensure high gains.

The process of creating a cryogenic layer of DT fuel with a highly uniform thickness inside of an ablator capsule, known as "layering" [Fig. 1], is essential in achieving high-yield implosions in an IFE system. In an IFE plant, capsules need to be filled and layered reliably, and at a low enough cost for successful plant economics, then injected into the target chamber before degradation of the uniform layer occurs. Due to the target symmetry requirements, and the exacting cryogenic conditions required to achieve that symmetry, layering is one of the top fundamental feasibility challenges for IFE.

Regardless of the target design (e.g., direct-drive, indirect drive, wetted foam, fast ignition, or drivers, laser technology, or ion beams), at the core of almost every implosion is a capsule that needs to be filled with DT fuel and cooled to temperatures below ~25 K. The DT layer needs to be highly uniform in thickness and the targets need to be individually handled to be transferred to an injection system.

2. Layering Requirements and Challenges

Strict symmetry requirements for the imploding fuel layer have been established during Inertial Confinement Fusion (ICF) experiments over the past couple of decades, but the processes applied to date are tailored for single-shot experiments and difficult to scale up. "Beta-layering" [Ref 1] may be used to redistribute DT from thicker areas within the capsule, where temperature from beta-decay is higher, to thinner areas (Fig 2). For beta-layering to be successful for IFE, the filled capsule must be kept in an extremely uniform temperature environment (~mK across the capsule). Therefore, simply placing many heat-producing DT capsules in a cold zone is insufficient. The uniform temperature must be maintained for a considerable length of time, up to hours depending on how "old" the tritium is (i.e., He-3 content from beta-decay) [Ref 2]. Externally applied infrared heating can speed up this process, but the difficulty of maintaining uniformity under heating may be a challenge[1]. For these reasons, cryogenic fluidized beds have been evaluated for direct drive IFE systems [Fig. 3]. The rapid circulation and spinning of the capsule provided within the fluidized bed provides a highly symmetric

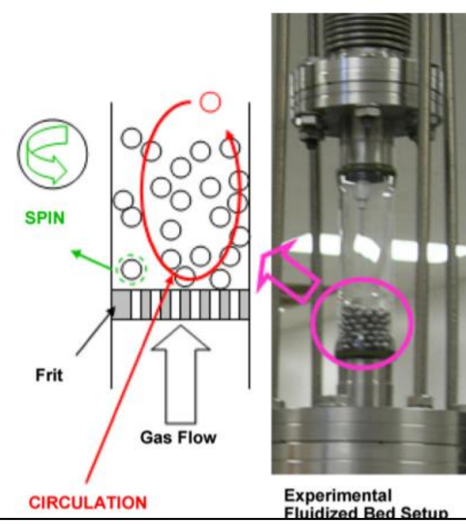

Figure 1: Spinning and circulating through the fluidized bed will ensure constant time-average temperature field on the capsule surface

[1] Externally applied IR radiation will also allow DD to be used in initial layering feasibility demonstrations, avoiding the need for tritium in initial testing.

“time-averaged” temperature for the DT-filled capsule to be layered [Ref 8].

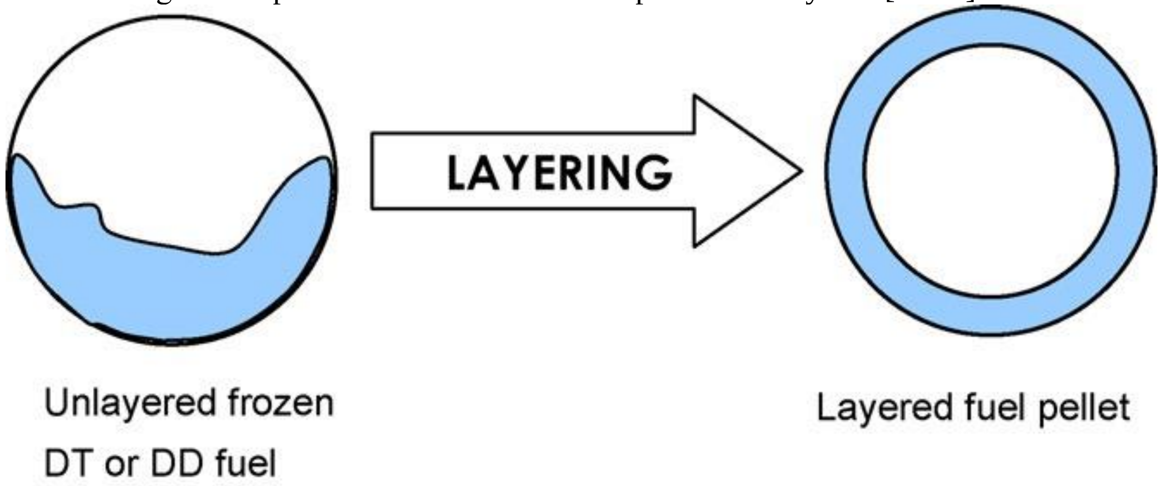

Fig. 2. Schematic illustration of the layering process. Frozen fuel initially accumulated on the bottom of the fuel pellet is redistributed into a layer of uniform thickness in an isothermal environment due to higher beta-decay heating and sublimation in thicker areas.

For indirect-drive IFE systems, it is possible to control the temperature environment of the capsule by tailoring the temperature of the surrounding hohlraum [Ref. 3, 4]. The challenge here is transferring this method to mass production. While the challenge of layering may be lessened if foam/liquid layer-targets [Ref. 5] could be used, credible layering concepts need to be developed for every target design that is considered for IFE.

2. Near-Term Research Opportunities

For the next 1–2 years, we propose to focus research and development on the following critical aspects of the target delivery process:

1) Different pathways to an IFE plant are currently being considered. While earlier programs like HAPL [Ref. 6] used a direct drive approach as a baseline, LIFE [Ref. 7] considered indirect drive. Other concepts like Fast Ignition [Ref. 9] are also proposed by the IFE community. In addition, different target designs are under consideration, such as wetted foam targets containing liquid or frozen DT. In each of these cases, the technology applied to create a thermal environment to grow uniform layers might be different. Concepts for layering targets of different geometries and complexity must be developed for a mass production setting for each of these paths, eventually including cost studies. The technology must be scaleable and result in reliable delivery of about 500,000 targets per day. Concepts need to be developed and vetted, leading to conceptual studies for the community to review. In parallel, small-scale hardware demonstrations for processes carrying the highest risk will be necessary, as was done previously under the HAPL program.

2) Concepts include filling of the capsule with DT through diffusion pressure or filling through small fill holes. Such holes need to be plugged either under pressure or at cryogenic temperatures. Mass-production methodologies for these need to be demonstrated, first at smaller scales. As well, rapid characterization of the layer through either optical means or X-Ray phase contrast imaging needs to be demonstrated.

3) The handling of individual targets and their transfer to an injection mechanism will be different depending on the baseline target design, but some consideration needs to be given to the cryogenic pick-and-place operation of targets after they have been layered. This includes ensuring that the thermal environment the target is exposed to during this operation does not destroy the layer symmetry.

Key metrics for this work include concept development and related feasibility evaluations of potential methodologies for mass-production layering. Layer symmetry achieved needs to be within tolerance for each target design. Faster layering times will reduce plant tritium inventory. Results must focus on feasibility information, for community review and consensus, for multiple IFE concepts. Small-scale demonstrations will use DD as a surrogate gas for tritium.

3. Long-Term Research Opportunities

Within the next 2–5 years, we expect the IFE community to settle on a baseline design, or a few minor variations, for an IFE power plant. The first phase of this program will evaluate all layering technologies for the different baseline options and provide data for a community down-select to a few minor variations. The second phase of this work will build a small-scale production line with sufficient throughput to demonstrate feasibility of technology based on the selection of a particular approach. This demonstration will not produce enough targets for an IFE power plant; however, the aim is to address the highest technological risks and demonstrate a scalable process that reliably produces targets of sufficient quality for power plant operation. Deuterium will be used as a surrogate for tritium. A further step is the integration of the layering system with the target injection, so that fuel layer survival can be checked post injection into a surrogate reactor chamber.

4. Strategy for Collaboration of HEDP, ICF, and IFE Communities

Development of a baseline design for an IFE power plant will require a coordinated effort from the entire IFE community. It will be based on input from not only the ICF and HEDP communities but also from material scientists, university researchers, laser manufacturers, and most other traditional engineering disciplines. Specifically as it relates to layering and target delivery systems, we will rely on subject matter experts from the ICF program in a number of areas.

First, the understanding of the layering process in all its intricacies has been greatly advanced as part of the ICF programs at Omega and NIF [Ref. 10]. The correlations of ice layer characteristics, e.g., grooves in single-crystal layers or non-uniformity of polycrystalline layers and the temperature field in spatial and temporal dimension, will be crucial in identifying suitable layering processes for an IFE plant. Extensive thermal modeling for behavior of layers inside indirect targets was performed in the ICF program.

Second, imaging a shell containing a layer, either through X-ray phase contrast or optical imaging, is key to characterizing the layer quality and demonstrating the viability of a layering process. In addition, image processing, i.e., understanding the quality of a layer based on the information contained in an image, is just as important. The layering program will also evaluate the liquid layer (foam capsules) studied in the ICF program. Evaluations will include the behavior of liquid layers during accelerations during injection into a power plant reactor chamber.

5. Technological Readiness

General Atomics (GA) was the main contributor in developing a prototypical target layering system for the High Average Power Laser (HAPL) program in 2006–2009. The baseline design in this program was a direct-drive target, and the target geometry was a ~4mm diameter sphere. Based on extensive initial calculations, a fluidized bed was identified as a viable option for mass-production layering. The underlying idea of this concept is that the shells will be cooled through a tightly temperature-controlled stream of helium gas. While the tritium heating of the fuel inside the shells will lead to a temperature gradient along the height of the bed, the random movement of the shells through the bed, and their rotation caused by collision with neighboring shells in the bed, will ensure a uniform time-averaged temperature outside the shell.

A cryogenic fluidized bed was constructed to hold about 700 shells. The bed was operated at temperatures as low as ~11 K, giving it sufficient margin to the typical layering temperature of 18–19.8 K. An infrared heating system was developed to simulate tritium heating, since the shells were filled with pure deuterium rather than a DT mix. The rotation and spin rates of the shells were measured and demonstrated to be sufficiently fast through a set of calculations and models. A High-Z coating (Au:Pd) is required on the shell surface to reduce radiation heat flux onto the target during chamber injection. There was concern that the coating would be damaged during fluidization. Initial data indicated fluidization parameters (combined with a sub-micron polymer overcoat) could be found to minimize damage to the outer surface while providing sufficient agitation to move the shells vertically through the bed. A permeation fill system was added to the cryostat, which enabled pressurization of ~100 shells to up to 17,000 psi and subsequent delivery of the shells into the fluidized bed. While layering, a single shell could be picked out of the bed and presented to a set of perpendicular optical cameras for inspection of the layer formation. However, funding ended before filled targets could be placed into the bed. Scale-up and further characterization of target quality is needed.

Liquid-filled foam capsules carry the promise to alleviate some of the challenges encountered for solid DT-ice layering. Relying on the effects of surface tension, the liquid DT is expected to wick into the pores of the foam, leading to very smooth inner layer surfaces. However, fuel uniformity requirements are passed on as foam layer uniformity requirements. Assuming a suitable foam capsule could be fabricated, one of the main areas of concern was the behavior of the liquid fuel during acceleration into the target chamber. In an effort to evaluate the behavior of liquid-filled foam shells during injection-type g-forces, a linear induction accelerator (LIA) was operated cryogenically. A liquid deuterium filled, wetted foam–layered capsule was exposed to 8000 g to verify that the acceleration did not cause liquid deuterium to drain out of the foam and pool at the bottom of the capsule. Images taken immediately upon exit from the accelerator show this was achieved, at least to the extent of the quality of the high-speed camera image, see Figure 4.

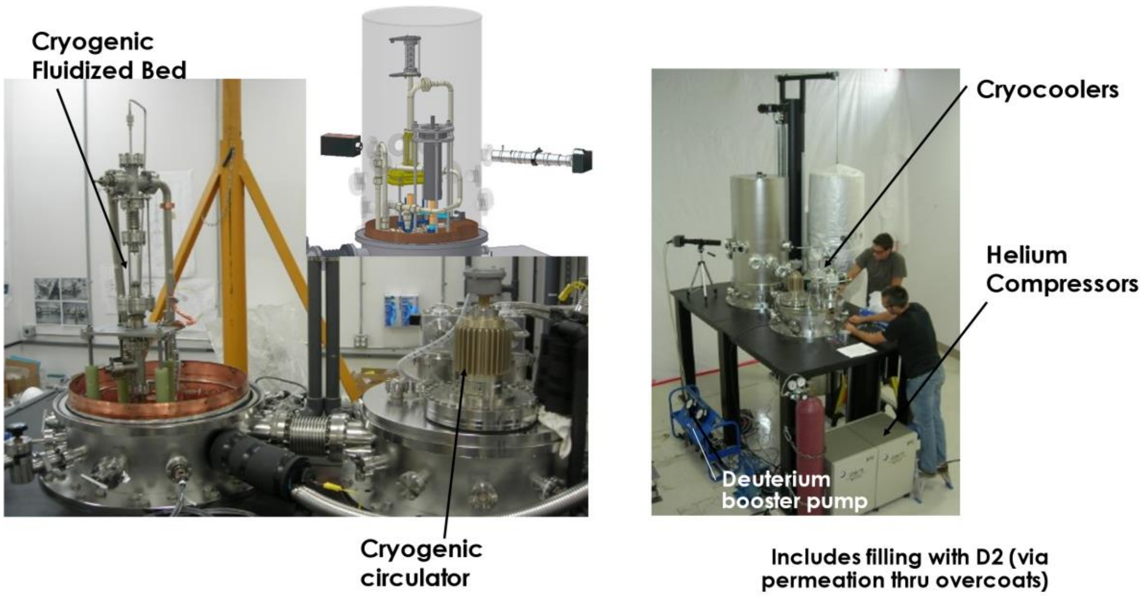

Figure 3: A cryogenic fluidized bed was assembled and operated at temperatures as low as 11 K for initial demonstration of a target layering concept for direct drive targets for the HAPL project.

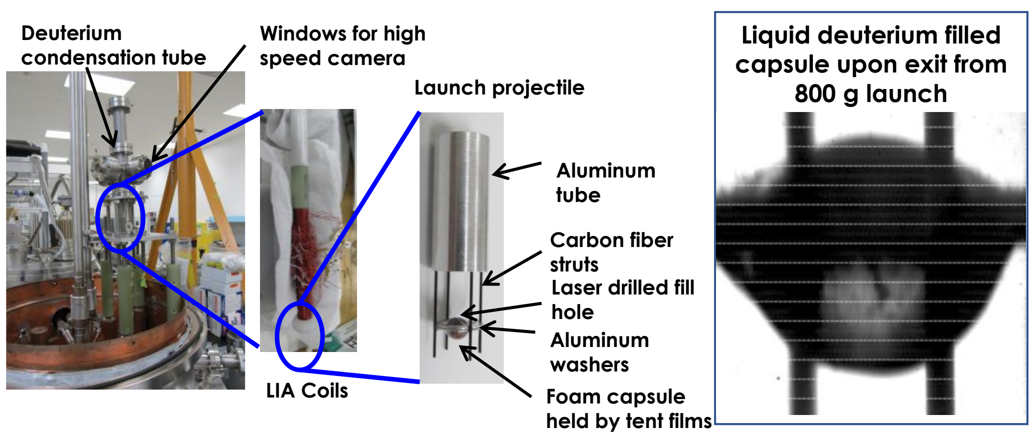

Figure 4: Left: Cryostat featuring a deuterium condensation tube, which contains LIA coils for launching projectile. A plastic overcoated foam capsule with fill hole oriented up is mounted inside the LIA. Struts on the projectile allow the foam capsule to be suspended in a pool of liquid deuterium at the bottom of the condensation tube for filling. Right: High speed (1000fps) camera image of filled wetted foam target immediately upon exit from 8000 g launch out of LIA. Note no obvious puddling of liquid deuterium at bottom of foam capsule despite acceleration forces.

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